

### **List of Figures**

FIGURE 1. IN-VEHICLE INSTALLATION GROUP	11
FIGURE 2. MULTIPLE GROUP INSTALLATION	12

### **List of Tables**

TABLE 1. DSRC MINIMUM RECEIVED SIGNAL LEVELS	3
TABLE 2. RSU TRANSMIT ISOLATION LEVELS	7
TABLE 3. BUS STOP BEACON SEPARATION DISTANCES IN FEET	17

## 1.0 INTRODUCTION

This paper presents sample calculations of DSRC frequency reuse distances for some DSRC installations developed in reference [1]. In this document, the DSRC system parameters and characteristics assumed are similar to the latest draft European DSRC standards [2]. However, in many cases the power levels vary significantly from the European standard to achieve the ranges needed for the US applications.

The particular objectives of this paper are the following:

1. To provide the theoretical basis and formulas for computing same channel frequency reuse distances,
2. To provide the theoretical basis and formulas for computing power levels that will prevent interference between DSRC beacons operating on different channels,
3. To calculate specific examples of frequency reuse distances and power levels using the formulas in (1) and (2) by making reasonable assumptions about the characteristics of the equipment involved, and

The specific calculations of reuse distances and power levels will be based on example installations of DSRC beacons from the main body of the report. The modulation format, data encoding and other communication parameters assumed in this paper were derived from the most recent draft European DSRC standards [2]. The European DSRC standard is adjusted to meet the requirements of the US DSRC systems. The pertinent communications link parameters of the DSRC systems from the spectrum requirement report and the European draft DSRC standards are as follows:

Downlink:	Modulation:	FM0 Encoded, ASK (On-Off Keying) (FM0 has transition at the beginning of each bit with and additional transition in the middle of a "0" bit.)
	Data Rate:	600 kbps
Uplink:	Modulation:	Binary and Quadrature Phase-Shift Keying (PSK)
	Data Rate:	600 kbps

The theoretical formulas for computing same and different channel power levels and separation distances required are presented in Section 2. Section 3 presents generic power level requirements and separation distance calculations similar to those in the European DSRC standards at 5.8 GHz [2]. The specific examples of frequency re-use distance calculations are presented in Section 4.

## 2.0 THEORY AND FORMULAS FOR CALCULATING INTERFERENCE POWER LEVELS AND SEPARATION DISTANCES

The calculation of minimum separation distance for either same channel or different channels begins with the calculation of transmit powers and required (minimum) received signal levels for successful downlink and uplink communications. Next, thresholds must be determined for the power levels of interfering signals. Finally, the propagation equations must be used to calculate minimum ranges meeting the interference thresholds. The calculations in this paper solve the minimum separation distance for same and adjacent channel operations because these are the worst case separation distances.

### 2.1 MINIMUM RECEIVED SIGNAL LEVEL CALCULATIONS

The Minimum Received Signal Level (MRSL) for a receiver is a function of the modulation used, data rate of the transmission, the Noise Figure (NF) of the receiver, and the required Bit Error Rate (BER) for the communications link. The modulation type and the data rate transmitted determine the bandwidth required by the receiver. Similarly, the modulation type and the required BER determine the required Signal-to-Noise Ratio (SNR) at the receiver. The formula<sup>1</sup> for calculating the MRSL of a receiver, expressed in dBm, is as follows:

$$MRSL = 10 * \log(k * T) + 10 * \log(B) + NF + SNR_{Req} + M \quad (1)$$

where  $k$  = Boltzman's constant =  $1.38 \times 10^{-23}$  joule/K,  
 $T$  = temperature in Kelvin = 290 K (typically),  
 $B$  = receiver bandwidth in Hz,  
 $NF$  = receiver noise figure in dB,  
 $SNR_{Req}$  = required SNR in dB to achieve desired BER, and  
 $M$  = communications link margin to allow for losses and multipath.

The maximum BER for the DSRC uplink and downlink is assumed to be  $10^{-6}$  to match the European DSRC standard [2]. Assuming that a simple noncoherent detection scheme is used, the required SNR for the ASK downlink is 17.2 dB. The required SNR for coherent PSK on the uplink is 10.5 dB to achieve a BER of  $10^{-6}$  [4].

The NF assumed for the DSRC systems to be evaluated here will be that of the GEC-Marconi TRICS system. The TRICS system operates at 5.8 GHz and its uplink receiver has a NF of 5 dB. No NF is quoted for the downlink. The IF (intermediate frequency) bandwidth of a PSK receiver is approximately twice the baud rate (rate at which the phase changes). The 250 kbps data rate uplink with NRZI encoding has a 250 kHz baud rate. Therefore, the PSK modulation at subcarrier frequencies of 1.5 kHz or 2 MHz, where each has a 250 kbps data rate, requires an IF bandwidth of approximately 500 kHz for a receiver tuned for either carrier. The quoted MRSL

---

<sup>1</sup> The noise factor formula in reference [3] was used as a basis for deriving this MRSL formula.

for the TRICS uplink receiver is -95 dBm (-125 dBW). Inserting these values into the above equation and solving for the link margin shows that the assumed link margin ( $M$ ) is 6.5 dB.

The MRSL for the DSRC investigated here can now be calculated by assuming the NF of the TRICS system and a similar link margin. The bandwidth of the DSRC uplink, calculated by assuming that the uplink data rate of each subcarrier is 300 kbps, is 600 kHz. Using the above equation, the MRSL of the uplink receiver in the Road Side Unit (RSU) is

$$MRSL = -204.0 + 57.8 + 5 + 10.5 + 6.5 = -124.2 \text{ dBW} = -94.2 \text{ dBm}$$

The MRSL for the DSRC downlink can be calculated similarly. However, the downlink receiver of the On-Board Unit (OBU) typically operates well above the MRSL. Thresholding is used to prevent the OBU from becoming active in the presence of very low signal levels. The European DSRC standard [2] set the MRSL of the downlink (OBU) at -40 dBm assuming a 0-dB-gain receive antenna. The threshold actually refers to the power density at the OBU rather than at the OBU receiver itself. If the OBU antenna has a gain,  $G$ , then the receiver's actual MRSL threshold must be -40 dBm +  $G$ . The threshold of -40 dBm will be used throughout this analysis.

The MRSLs assumed for the DSRC for the remainder of this paper are listed in Table 1.

**Table 1. DSRC Minimum Received Signal Levels**

Receiver	Minimum Received Signal Level
Uplink Receiver (RSU)	-94 dBm
Downlink Receiver (OBU)	-40 dBm (0 dB receive antenna)

## 2.2 DOWNLINK TRANSMIT POWER REQUIREMENTS

The power received by any particular receiver,  $P_R$ , can be calculated using the following formula:

$$P_R = \frac{P_T * G_T * G_R * \lambda^2}{(4 * \pi)^2 * R^2} \quad (2)$$

where:  $P_T$  = Transmit power in Watts,  
 $G_T$  = Transmit antenna gain in the direction of the receiver,  
 $G_R$  = Receive antenna gain in the direction of the receiver,  
 $\lambda$  = Wavelength of the transmitted signal, and  
 $R$  = Range between the transmit and receive antennas.

The required transmit power,  $P_T$ , can be calculated by letting the received power equal to the MRSL of the receiver and solving the equation for  $P_T$ . The resulting equation is as follows:

$$P_T = \frac{MRSL * (4 * \pi)^2 * R^2}{G_T * G_R * \lambda^2} \quad (3)$$

Note that it is often more efficient to calculate these values in dB, especially in spreadsheets. Most of the calculations done in this effort were accomplished using spreadsheets and thus were done in dB. The above equation expressed in dB is

$$P_T = MRSL + 20 \log(4 * \pi) + 20 \log(R) - G_T - G_R - 20 \log(\lambda) \quad (4)$$

where  $P_T$ ,  $G_T$ ,  $G_R$  and  $MRSL$  are all expressed in dB.

The DSRC downlink transmit power is calculated using the MRSL thresholds listed in Table 1. Assuming the receive antenna gain is 0 dB ( $G_R = 0$  dB), the required transmit power for a successful downlink in dBm is

$$P_{t\_d} = OBU\_min + 2 * F\_PI + 2 * Rmax\_dB - (RSU\_g - RSU\_gl) - 2 * Lambda\_dB \quad (5)$$

where:  $P_{t\_d}$  = Transmit power required for successful downlink in dBm,  
 $OBU\_min$  = -40 dBm = MRSL of OBU assuming 0 dB antenna,  
 $F\_PI$  =  $10 \log(4 * \pi)$ ,  
 $Rmax\_dB$  =  $10 \log(\text{maximum range, } Rmax, \text{ in feet})$ ,  
 $RSU\_g$  = Peak Gain of RSU antenna in dB,  
 $RSU\_gl$  = RSU antenna pattern shape loss (assumed to be 3 dB for edge of main lobe, and  
 $Lambda\_dB$  =  $10 \log(\lambda)$ , where  $\lambda$  is expressed in feet.

The variable names used in equation 5 are those used in the spreadsheets later in this paper.

### 2.3 DOWNLINK TRANSMIT POWER REQUIRED FOR SUCCESSFUL UPLINK

The DSRC OBU is assumed to be a semi-active transceiver. It simply modulates a carrier tone transmitted from the RSU by mixing the tone with a PSK modulated subcarrier at 1.8 MHz or 2.4 MHz. The resulting signal is then amplified with a 10 dB gain amplifier and retransmitted to the RSU. Since the uplink transmission is a modulated and amplified reflection of a downlink tone, then the received signal level of an uplink is a function of the downlink transmit power.

The signal power received by the OBU is modulated and reflected back to the RSU with some losses and gains inherent in the OBU. To determine the sum total of the losses and gains due to the OBU, the assumption used in the European DSRC standard [2] will be used in this analysis. The European DSRC standard assumes that the OBU antenna has a gain ( $OBU\_g$ ) of 4 dB up to 35 degrees off boresight, a one-way transmission loss through the windscreen ( $L\_w$ ) of 3 dB, a modulation loss ( $L\_m$ ) of 3 dB (due to on-off keying) and a realization loss ( $L\_r$ ) of 4 dB. The OBU also has a 10 dB RF amplifier ( $OBU\_rf$ ). The transmitted signal level (including antenna gains) from the OBU relative to the received power level (assuming 0 dB antenna gain) is called

the minimum conversion gain ( $OBU\_Gain$ ). The minimum conversion gain is calculated:  
 $OBU\_Gain = 2*OBU\_g + OBU\_rf - 2*L_w - L_m - L_r = +5 \text{ dB}$ .

The power received by the OBU can be calculated using equation 2. The OBU antenna gain can be considered as 0 dB because the antenna gain is included in  $OBU\_Gain$ . The power transmitted back to the RSU is calculated by adding  $OBU\_Gain$  to the received signal level at the OBU. Finally, the received signal level at the RSU is calculated by again using equation 2 for the return link. The required transmit power for a successful uplink is that which results in a received signal level at the RSU equal to the MRSL. The transmit power required for a successful uplink,  $Pt\_u$ , in dBm can be expressed as

$$Pt\_u = RSU\_mrsl + 4 * F\_PI + 4 * Rmax\_dB - OBU\_gain - 2 * (RSU\_g - RSU\_gl) - 4 * Lambda\_dB \quad (6)$$

where:  $RSU\_mrsl$  = uplink MRSL in dBm.

The required RSU transmit power for a given operating range,  $Pt$ , is the maximum of  $Pt\_d$  and  $Pt\_u$ .

## 2.4 SEPARATION DISTANCE CALCULATIONS

The required separation distance between transmitters and receivers is a function of the maximum allowable interference level at the receiver, the transmit and receive antenna gains in the direction of transmission, the transmit power levels, and the isolation between the transmitted signal and the received frequency bands.

The transmit power levels are determined by the required operating ranges and antennas for a given scenario. The equations for determining the required transmit power level were presented in Section 2.3. Each of the remaining parameters is discussed in the following sections, followed by derivation of the equations for calculating minimum required separation distances.

### 2.4.1 Maximum Allowable Received Interference Level

The maximum allowable received interference levels assumed in the analysis were derived from the European DSRC standard [2] and the MRSL of the GEC-Marconi TRICS system. The European DSRC standard quotes an RSU maximum interference level of -115 dBm (-135 dBm plus a 20 dB antenna gain). This level is 20 dB below the MRSL quoted for the TRICS system. Since the MRSL for the RSU of the DSRC system assumed for this analysis is -94 dBm, then the assumed maximum RSU interference level,  $RSU\_int$ , is assumed to be 20 dB lower or -114 dBm.

The downlink MRSL is assumed to be the same as that quoted in the European DSRC standard (-40 dBm) and thus the maximum interference level is also assumed to be the same. The maximum received interference level at the OBU,  $OBU\_int$ , is therefore assumed to be -60 dBm, assuming a 0 dB gain OBU antenna.

### 2.4.2 Antenna Gain and Sidelobe Levels

The RSU antenna gains assumed in each of the scenarios in Section 4 are calculated from the elevation and azimuth beamwidths required for the RSU to cover its intended area on the road. The geometry of the scenario determined the azimuth and elevation beamwidths of the antenna which then were translated to antenna gain.

The gain of an RSU antenna,  $RSU\_g$ , can be expressed in terms of the area of the aperture,  $A$ ; the aperture efficiency,  $\rho_a$ ; and the wavelength,  $\lambda$ , as follows: [5]

$$RSU\_g = \frac{4 * \pi * A * \rho_a}{\lambda^2} \quad (7)$$

The area of the aperture (assumed rectangular) can be calculated

$$A = d_a * d_e, \quad (8)$$

where  $d_a$  and  $d_e$  are the dimensions of the aperture in the azimuth and elevation directions, respectively. The European DSRC standard [2] assumes that the gain of the RSU antenna sidelobes are 15 dB ( $RSU\_sl$ ) below the peak of the main lobe. A parabolic energy distribution across an antenna aperture can produce an antenna pattern with sidelobes 15.8 dB below the peak antenna gain. The aperture efficiency of this aperture distribution is 0.994 and the beamwidth of the antenna in degrees is

$$RSU\_az,el = \frac{53 * \lambda}{d_{a,e}} \quad [4] \quad (9)$$

By substituting equation 8 and 9 into 7, an equation for antenna gain as a function of antenna beamwidth becomes

$$RSU\_g = 10 \log \left( \frac{4 * \pi * 0.994 * 2809}{RSU\_az * RSU\_el} \right) \quad (10)$$

For the purposes of this analysis, the OBU antenna is usually assumed to have a very wide beamwidth and unknown orientation. Therefore, unless otherwise stated, it is assumed that the interference from or to an OBU is assumed to be transmitted through the main lobe of the OBU antenna. The gain of the OBU antenna,  $OBU\_g$ , is assumed to be 4 dB as in the European DSRC standard [4].

### 2.4.3 Isolation Specifications for Same and Adjacent Channels

The isolation described in this section is due to the frequency differences (spectral masking) between the various transmitted signals. They are derived from the European DSRC standard [2] and translated for use in the DSRC system assumed for use in the US.

The downlink (RSU) isolation or spectral masking listed in the European standard is presented in terms of total EIRP (Effective Isotropic Radiated Power) in a bandwidth and is based on an assumed maximum transmitted EIRP of +33 dBm. For use in this analysis, the spectral masking is used as an isolation between the transmitted signal and another signal frequency band. The European standard specifications for interference are listed as maximum allowable power in particular bands. The Isolation specifications used for the proposed US DSRC systems were calculated from the European specifications by subtracting the allowable power in each band from the peak in-band power allowed by the European specifications.

The RSU transmissions include a tone for the OBU to modulate and an ASK modulated downlink signal. The spectrum mask standards are divided into three classes (A, B and C) with increasing levels of isolation. No reason is stated for the three classes in the European standard, but their existence would allow short range low power systems to operate with less sophisticated equipment than longer range systems. The RSU downlink isolation for the tone and each class of modulated downlink are listed in Table 2.

**Table 2. RSU Transmit Isolation Levels**

Class	Description	Label	Isolation (dB)
Tone	To Lower Uplink Band	RSU_TL	60
	To Upper Uplink Band	RSU_TU	60
	To Adjacent Channel	RSU_TA	80
Class A	To Lower Uplink Band	RSU_AML	40
	To Upper Uplink Band	RSU_AMU	60
	To Adjacent Channel	RSU_AMA	63
Class B	To Lower Uplink Band	RSU_BML	50
	To Upper Uplink Band	RSU_BMU	60
	To Adjacent Channel	RSU_BMA	70
Class C	To Lower Uplink Band	RSU_CML	60
	To Upper Uplink Band	RSU_CMU	60
	To Adjacent Channel	RSU_CMA	80

There is little spectral masking that can be done to the OBU emission in order to reduce unwanted energy in other channels. A filter cannot be used since the frequency changes depending on the beacon frequency. Only shaping (smoothing) of the amplitude variations can reduce the unwanted images of the PSK signal produced by the amplitude modulation. Very little (3 dB) isolation is specified in the European standard between the uplink bands and the downlink bands in the same channel and thus no isolation is assumed for this analysis. The only isolation specification of



significance is isolation between adjacent channels, *OBU\_AI*, which is specified at 18 dB (-24 dBm maximum EIRP and -42 dBm maximum emissions in adjacent channels).

#### 2.4.4 Calculating Minimum Separation Distance

The formula required to calculate minimum separation distances is a modification of equation 4 to account for isolation, antenna sidelobe levels (where needed) and actual maximum transmit powers. The generic formula for calculating minimum separation distance is

$$R_{sep} = 10^{\left[ \left( Pt + Gt + Gr - Isol + 2 * Lambda\_dB - 2 * F\_PI - P_{int} \right) / 10 \right]} \quad (11)$$

where:  $R_{sep}$  = Minimum required separation distance in feet,  
 $Pt$  = RSU transmit power or maximum OBU transmit power in dBm,  
 $Gt$  = Gain of the transmit antenna in dB, and  
 $Isol$  = Isolation between bands of interest in dB.

Note that the European specifications limit the EIRP transmitted by the OBU (including antenna gain and windshield losses) to -24 dBm. It is assumed in the separation distance calculations that the OBU limits its output EIRP to -24 dBm. This limiting or automatic gain control (AGC) is assumed to prevent OBU output EIRP from exceeding -24 dBm regardless of received signal power.

### 3.0 GENERIC CALCULATIONS OF TRANSMIT POWER AND SEPARATION DISTANCE

As an initial step to determining minimum separation distances between DSRC system, a generic or worst-case analysis is performed. For this analysis, it is assumed that all OBU and RSU transmitters are operating at maximum power.

Applying the specifications from the European standard [2] yields a maximum OBU transmit EIRP of -24 dBm. The maximum EIRP for the RSU is calculated by assuming a 20 dB antenna gain and a maximum operating range of 50 feet. This yields a maximum transmit power ( $P_t$ ) of 14.44 dBm or an RSU EIRP ( $RSU\_P_{max}$ ) of 34.4 dBm.

The calculations of the minimum separation distances are shown in the spreadsheet in Appendix A. The bold values in the spreadsheets are those manually entered into the spreadsheet while the normal values are those calculated by equations within the spreadsheet.

The separation distances are calculated between all antennas, for all classes of RSU transmitters, between all frequency bands in a channel, and between adjacent channels. The separation distances are calculated assuming interference through the mainlobes and sidelobes of the RSU antennas. The distances calculated are between two DSRC systems with the same characteristics.

The separation distances calculated in Appendix A are labeled according to their direction of transmission. Therefore an uplink on downlink separation distance is the separation distance between a transmitting OBU (uplink) from one DSRC system and an OBU receiving data (downlink) from another DSRC beacon. Similarly, the uplink on uplink separation distance is the required separation distance between a transmitting OBU (uplink) responding to one RSU and a different receiving RSU (uplink).

The calculated separation distances in Appendix A vary from almost 8,000 feet to less than 1 foot depending on which combination of transmitter and receivers are being analyzed, whether RSU antenna sidelobe or mainlobe is assumed, or whether same channel or different channels are assumed. The longest required separation distances are the downlink (RSU transmitter) on uplink (RSU receiver) distances, particularly those in the RSU antenna main lobe. The reduced isolation of the Class A RSU transmitter is evident in the longer required downlink on uplink separation distances.

The next longest separation distances calculated were in the uplink (OBU transmitter) on uplink (RSU receiver). The required separation between an RSU and an interfering OBU operating in the same channel and in its main lobe was calculated to be over 4000 feet. Even if the OBU was operating in the RSU antenna's sidelobes, the calculated separation distance required was over 750 feet.

This general analysis is useful determining basic guidelines on separation of DSRC systems. However, the specific implementation or deployment of the system could drastically affect the minimum required separation distance. Section 4 will demonstrate calculations of minimum separation distances for some specific same-channel and different-channel DSRC systems.

## 4.0 SPECIFIC SEPARATION DISTANCE CALCULATIONS

Further information on implementation and minimum required separation distances can be gleaned by investigating specific deployments of DSRC systems and determining required separation distances. In this section, five specific examples of separation distance calculations will be performed. These examples are all from example installation groups of DSRC systems in the updated study on DSRC spectrum requirements. main body of the report.

For each specific example, a spreadsheet was developed to calculate same channel and adjacent channel separation distances. The spreadsheets for each example are included in Appendices to this report. The RSU antenna gain and transmit power for each DSRC system were calculated to meet the coverage area requirements. Then it was determined whether or not the interference paths were through the mainlobe or the sidelobe of the RSU and OBU antennas. For cases where the two DSRC systems have different characteristics (coverage area, power, antenna gains, . . .), all combinations of interference between the two systems are assessed.

The first two example calculations in Section 4.1 and 4.2 are from the In-Vehicle Signing Installation Group explained in [1]. The In-Vehicle Signing Installation Group is shown in Figure 1. In Section 4.1, the minimum separation distances will be calculated to prevent interference between an in-vehicle signing beacon along the highway and an exit beacon. In Section 4.2, minimum separation distances between two identical in-vehicle signing beacons will be calculated.

The separation distance calculations in Section 4.3 to 4.5 refer to beacons in the Multiple Group Installation explained in [1]. The Multiple Group Installation is shown in Figure 2. The separation distance calculations between 2 identical intersection beacons (beacons J and P in Figure 2) are discussed in Section 4.3. In Section 4.4, the separation distance between identical bus stop beacons (beacons Y, Z and AA in Figure 2) are calculated. Lastly, in Section 4.5, the interference issues and separation distances between an off-line verification beacon (beacon W) and intersection beacon (such as beacon P) are evaluated.

In each of the examples below it is assumed that both DSRC systems are operating either at the same time or independently. In other words, there is no time multiplexing or coordination between the beacons that could reduce or eliminate the possibility of interference. In some cases, the communications requirements prohibit coordination while in other cases the separation distance calculation may indicate the need for time multiplexing or coordination. These issues will be discussed as needed in the analysis of the separation distance calculations. If time multiplexing is required, the capture zone can be lengthened so that the required data rate is not increased.

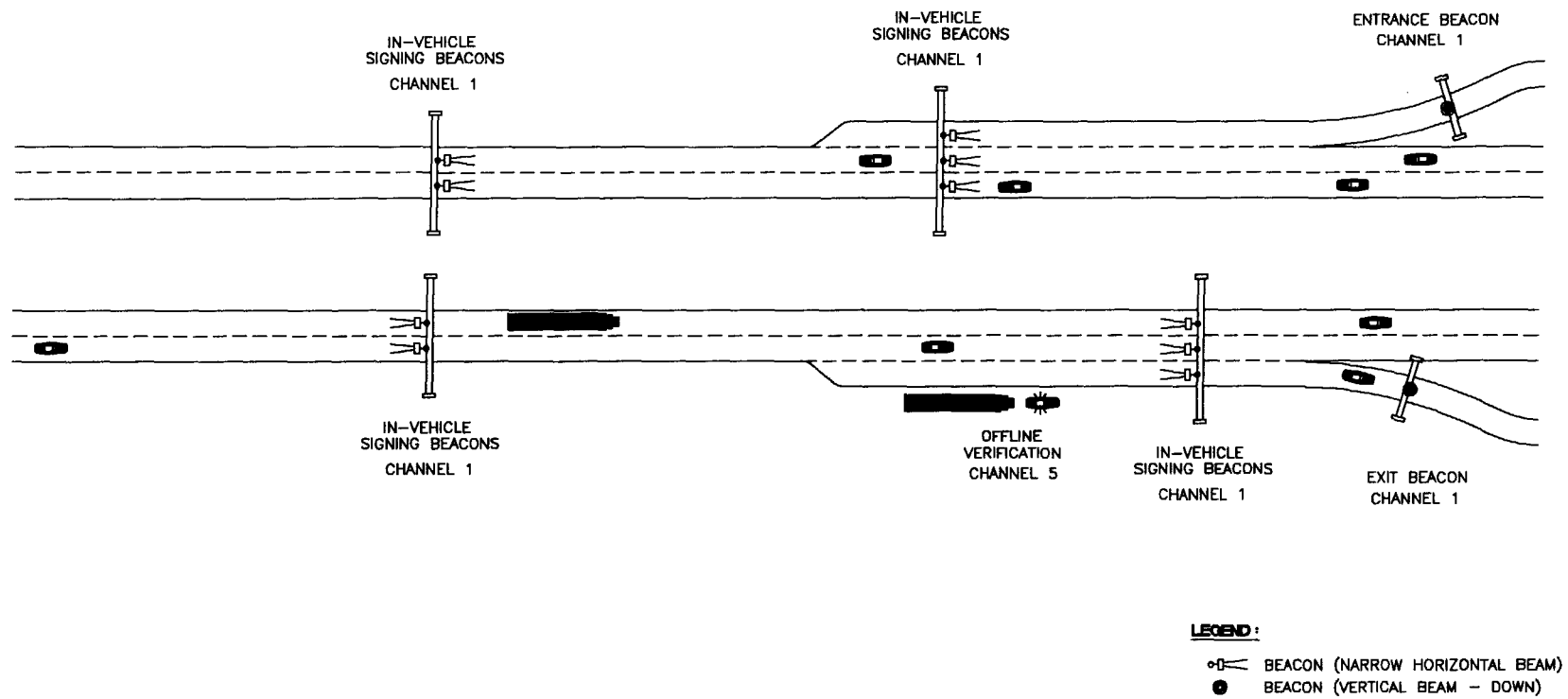


Figure 1. In-Vehicle Signing Installation Group (with channel assignments)

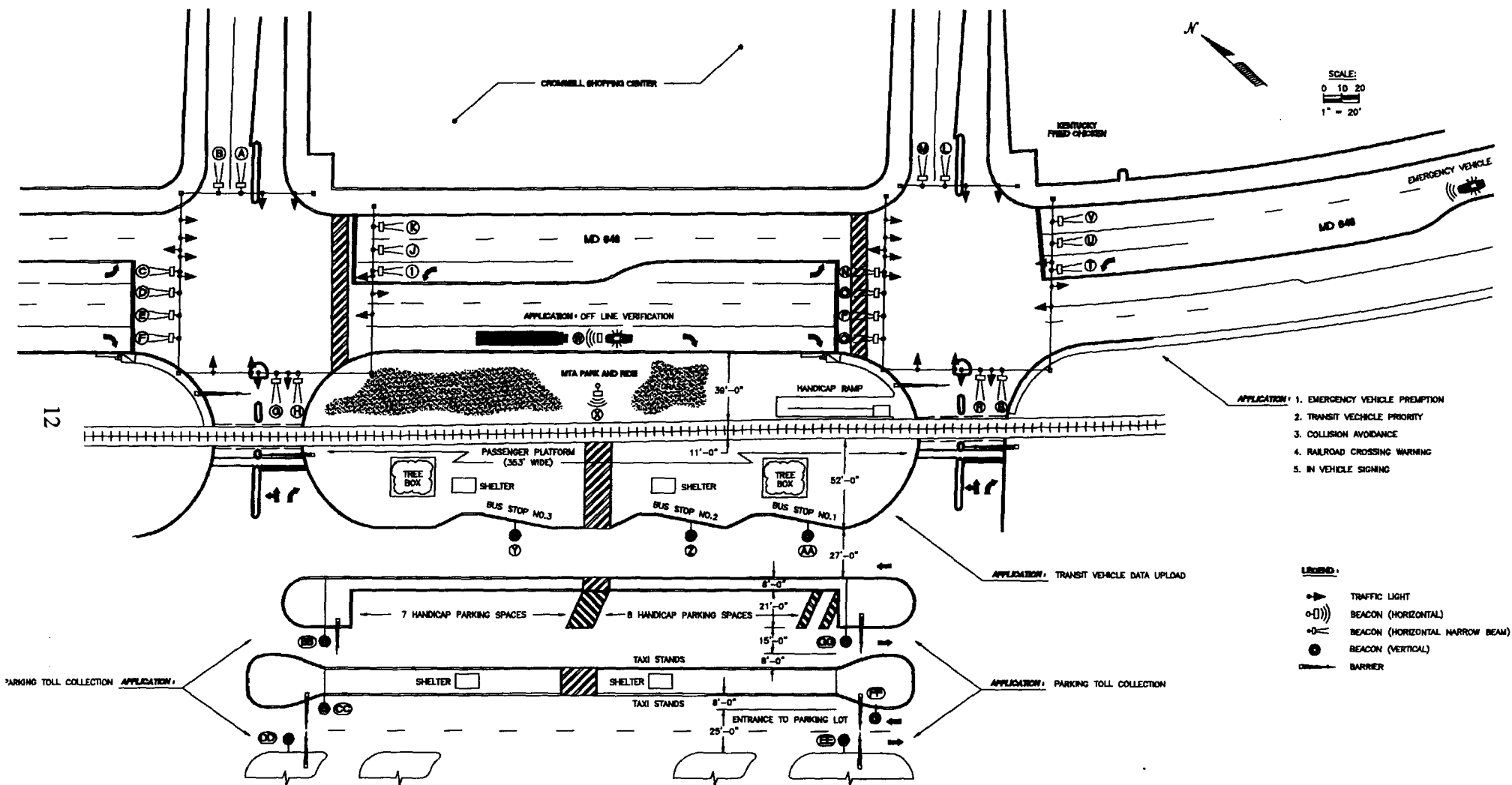


Figure 2. Multiple Group Installation

## 4.1 IN-VEHICLE SIGNING TO EXIT BEACONS

The separation distances required between an in-vehicle signing beacon and an exit beacon in Figure 1 are evaluated in this section. Several assumptions have been made in determining the characteristics of the beacons. The assumptions for the in-vehicle signing beacon (Beacon 1) are as follows:

- The RSU beacon is mounted 20 feet off the road centered on a lane,
- The maximum distance down the road covered by the beacon is 50 or 100 feet,
- The minimum angle of the beam of the RSU antenna is 45 degrees from vertical,
- The 3 dB width of the RSU beacon's antenna beam at the longest range is 12 feet, and
- The height of the OBU is 5 feet.

The assumption for the exit beacon (Beacon 2) are as follows:

- The RSU beacon is mounted 20 feet off the road centered on an exit lane,
- The RSU antenna is pointed downward covering a 30 foot length of road 12 feet wide, and
- For purposes of determining maximum OBU transmit power, the minimum link range is assumed to be 12 feet.

The OBU is assumed to have an average height of 5 feet for both DSRC beacon systems.

### 4.1.1 Results Assuming a 50 Foot Range for the In-Vehicle Signing Beacon

The calculations of minimum separation distances for this example assuming a 50 foot range on the in-vehicle signing beacon are shown in the spreadsheet in Appendix B-1. Beacon 1 is the in-vehicle signing beacon and Beacon 2 is the exit beacon. It is assumed that all interference from or to either RSU is through the RSU sidelobes since the intended coverage areas of each beacon are physically separated. The separation distances are calculated for each combination of transmitter and receiver. For example, an uplink on uplink calculation under the column labeled "2 on 1" is the separation distance required between the OBU transmitter operating with Beacon 2 and the RSU receiver of Beacon 1.

Figure 1 indicates that the in-vehicle signing beacons and the exit beacons will likely be operating on the same frequency. From the spreadsheet in Appendix B-1, the largest calculated same-channel separation distances are due to the Class A modulated downlink from the in-vehicle signing beacon on the uplink receiver of the exit beacon. The minimum separation distance is 629 feet for this case. Using a Class B or C RSU transmitter does not result in significantly lower separation distances because the minimum separation distance is limited by the same channel uplink on uplink. The separation distance required between an OBU responding to the exit beacon and an in-vehicle-signing RSU receiver operating at the same frequency is 515 feet. Therefore, the minimum separation distance for same channel operation is about 515 feet.

If the exit beacon must operate much closer than 515 feet, then different (possibly adjacent) channels must be used. The spreadsheets in Appendix B-1 indicate that the minimum separation distance between the beacons is 65 feet (limited by uplink on uplink separation).

#### **4.1.2 Results Assuming a 100 Foot Range for the In-Vehicle Signing Beacon**

The calculations of minimum separation distances for this example assuming a 100 foot range on the in-vehicle signing beacon are shown in the spreadsheet in Appendix B-2. The results are very similar to those discussed in Section 4.1.1.

The largest same channel separation distance calculated in Appendix B-2 is 1226 feet for the Class A modulated downlink from the in-vehicle signing beacon on the exit beacon RSU receiver (downlink on uplink). If Class B or C RSU transmitters are used for the beacons, the limiting factor becomes the separation required between an OBU responding to the exit beacon and an in-vehicle signing beacon RSU (uplink on uplink). Therefore, the minimum separation distance required between an in-vehicle signing beacon (OBU or RSU) and an exit beacon operating in the same channel is 631 feet.

If different or adjacent channels are used, the separation distance can be reduced considerably. If Class A RSU transmitters are used for the in-vehicle signing beacon then the separation distance required is limited by downlink (in-vehicle beacon RSU) on uplink (exit beacon RSU) to about 87 feet. If Class B or C RSU transmitters are assumed, the minimum separation range is limited by uplink on uplink to about 79 feet.

### **4.2 IN-VEHICLE SIGNING BEACONS ALONG A HIGHWAY**

In this section, the minimum separation distances between two in-vehicle signing beacons in Figure 1 are calculated. The assumptions used to define the beacons are the same as the in-vehicle signing beacon in Section 4.1. For this example it is assumed that the beacons have distinct coverage areas and thus all interference involving an RSU transmitter or receiver is through the sidelobes of the RSU antenna.

#### **4.2.1 Results Assuming a 50 Foot Range In-Vehicle Signing Beacons**

The results of the 50 foot range in-vehicle signing beacon same channel minimum separation distance calculations are shown in the spreadsheet in Appendix C-1. The minimum separation distance between in-vehicle signing beacons is again limited by the downlink (RSU transmitter) on uplink (RSU receiver) interference assuming Class A RSU transmitter specifications are assumed. The minimum separation distance calculated is 1,136 feet for the Class A RSU transmitters. If the Class B or C RSU transmitter isolation specifications are assumed the minimum separation distance is limited to 717 feet by the uplink (OBU transmitter) on uplink (RSU receiver) interference.

The same channel minimum separation distances calculated for in-vehicle signing beacons are not unreasonable to implement for most cases. However, if smaller separation distances are needed, then use of separate (or adjacent) frequencies can reduce the minimum separation distance to 114

feet assuming Class A transmitter parameters are used. If Class B or C RSU transmitters are used, then the adjacent channel separation distance is limited a minimum of 90 feet by the uplink on uplink separation requirements.

#### **4.2.2 Results Assuming a 100 Foot Range In-Vehicle Signing Beacons**

The results of the 100 foot range in-vehicle signing beacon same channel minimum separation distance calculations are shown in the spreadsheet in Appendix C-2. The minimum separation distance between in-vehicle signing beacons is again limited by the downlink (RSU transmitter) on uplink (RSU receiver) interference assuming Class A RSU transmitter specifications are assumed. The minimum separation distance calculated is 2,710 feet for the Class A RSU transmitters. If the Class B or C RSU transmitter isolation specifications are assumed the minimum separation distance is limited to 896 feet by the uplink (OBU transmitter) on uplink (RSU receiver) interference.

The same channel minimum separation distances calculated for in-vehicle signing beacons are again not unreasonable to implement for most cases. However, if smaller separation distances are needed, then use of separate (or adjacent) frequencies can reduce the minimum separation distance to 192 feet assuming Class A transmitter parameters are used. If Class B or C RSU transmitters are used, then the adjacent channel separation distance is limited a minimum of 113 feet by the uplink on uplink separation requirements.

### **4.3 INTERSECTION BEACONS**

Beacons operating at intersections are similar in configuration to in-vehicle signing beacons. They generally do have to cover wider areas (more lanes) and in dense urban environments may have overlapping coverage areas. The minimum separation distance calculations for this example are based on the intersection beacons J and P in Figure 2. The assumptions for these beacons are as follows:

- The RSU beacon is mounted 20 feet off the road centered on a lane,
- The maximum distance down the road covered by the beacon is 50 or 100 feet,
- The maximum angle of the beam of the RSU antenna is 90 degrees from vertical (horizontal) to allow for the reception of longer range emergency vehicle OBUs,
- The minimum angle of the beam of the RSU antenna is 30 degrees from vertical,
- The width of the RSU beacon's antenna beam at the longest range is 12 feet with 1 antenna per lane approaching the intersection , and
- The height of the OBU is 5 feet.

The coverage area for the intersection beacons is very similar to in-vehicle signing beacons. The intersection beacons only differ in the fact that the minimum angle of the intersection beacon is 30 degrees from vertical (as opposed to 45 degrees for the in-vehicle signing beacons). For this example, the antenna pattern is assumed to be elliptical as one would expect from a rectangular aperture antenna.



#### **4.3.1 Results Assuming 50 Foot Range Intersection Beacons**

The results of the minimum distance calculations for intersection beacons with 50 foot maximum operating ranges are listed in the spreadsheets in Appendix D-1. The calculations in the spreadsheet included minimum separation distances assuming the interference was received or transmitted through the RSU antenna mainlobe and sidelobe. A quick check of the calculations shows that even assuming adjacent channel interference, the minimum separation distance between RSU antennas calculated for mainlobe interference is 356 feet (uplink on uplink assuming Class C RSU transmitters). This is almost the same as the separation distance between beacons J and P in Figure 2. Therefore, the implementation of intersection beacons must ensure that the RSU antennas do not include in their main lobe OBUs responding to another intersection beacon. This is consistent with the 50 foot range of the intersection beacons and the scenario shown in Figure 2.

Assuming that the RSU antennas of nearby beacons are not directed at one another (separated coverage areas), then the minimum separation distance between beacons operating in adjacent channels is 63 feet. The minimum separation distance is limited by the uplink (OBU transmitter) on uplink (RSU receiver). The separation distance between intersection beacons J and P in Figure 2 is over 300 feet. Therefore, the minimum separation distance is met between these beacons for adjacent channels. Beacons A and J in Figure 2 are only separated by 65-70 feet. These beacons barely meet the minimum separation requirements and it may be advisable to time multiplex these beacons to avoid interference, even if operating on different frequencies.

If the intersection beacons are operating in the same channel, then the minimum separation between RSU antennas is 780 feet for Class A RSU transmitters. Class B and C RSU transmitters must be separated by 503 feet (uplink on uplink). These results indicate clearly that any two intersection beacons operating at the same frequency from a single intersection must be time multiplexed in order to avoid interference. Also, closely spaced intersections with beacons using the same frequencies at both intersections must also be time multiplexed.

#### **4.3.2 Results Assuming 100 Foot Range Intersection Beacons**

The results of the minimum distance calculations for intersection beacons with 100 foot maximum operating ranges are listed in the spreadsheets in Appendix D-2. The calculations in the spreadsheet included minimum separation distances assuming the interference was received or transmitted through the RSU antenna mainlobe and sidelobe. A quick check of the calculations shows that even assuming adjacent channel interference, the minimum separation distance between RSU antennas calculated for mainlobe interference is 857 feet (downlink on uplink assuming Class C RSU transmitters). This is well over twice the separation distance between beacons J and P in Figure 2. Therefore, the implementation of intersection beacons must ensure that the RSU antennas do not include other RSU antennas in their main lobe. This is consistent with the 100 foot range of the intersection beacons and the scenario shown in Figure 2.

Assuming that the RSU antennas of nearby beacons are not directed at one another (separated coverage areas), then the minimum separation distance between beacons operating in adjacent channels is 88 feet assuming Class B or C RSU transmitters. The minimum separation distance is

limited by the uplink (OBU transmitter) on uplink (RSU receiver). The separation distance between intersection beacons J and P in Figure 2 is over 300 feet. Therefore, the minimum separation distance is met between these beacons for adjacent channels. Beacons A and J in Figure 2 are only separated by 65-70 feet. The separation between these beacons does not meet the minimum separation requirements and therefore time multiplexing of these beacons is required to avoid interference, even if operating on different frequencies.

If the intersection beacons are operating in the same channel, then the minimum separation between RSU antennas is 2,710 and 857 feet for Class A and B RSU transmitters, respectively. Class C RSU transmitters must be separated by 699 feet (limited by uplink on uplink). These results indicate clearly that any two intersection beacons operating at the same frequency from a single intersection must be time multiplexed in order to avoid interference. Also, even moderately closely spaced intersections with beacons using the same frequencies at both intersections must also be time multiplexed.

#### 4.4 BUS STOP BEACONS

Beacons Y, Z and AA in Figure 2 are bus stop beacons spaced fairly close together. The separation distances between the beacons are shown in Table 3. These beacons are assumed for this analysis to be operating independently and often communicating large amounts of information between the OBU on the bus and the RSU.

**Table 3. Bus Stop Beacon Separation Distances in Feet**

Beacon	Y	Z	AA
Y	N/A	100	167
Z	100	N/A	66
AA	167	66	N/A

The assumptions for the RSU and OBU in the Bus Stop scenario are as follows:

- The RSU beacon is mounted 20 feet off the road,
- The height of the OBU antenna is between 12 and 15 feet yielding a 5 to 8 foot operating range for the link,
- The RSU antenna is designed to cover a 8 x 8 foot area at a distance of 8 feet,
- The OBU antenna is mounted on the top of the bus directed vertically, and
- The sidelobes of the OBU antenna are 15 dB below the peak antenna gain (special shielding on the OBU antennas may be required, or a custom antenna).

In this scenario, the OBU antennas are assumed to have a known location and orientation on the vehicles (busses). The OBU antennas are directed straight upward and designed only to communicate with vertical beacons. Therefore, interference from other RSUs or OBUs is assumed to only be possible through the sidelobes of the OBU antennas.

The results of the minimum separation distance calculations are listed in the spreadsheet in Appendix E. The calculations include same channel and adjacent channel minimum separation distance calculations. The minimum same channel separation distance is 120 feet assuming Class A RSU transmitters. The distance is reduced to 57 feet for Class B or C RSU transmitters (limited by the uplink on uplink minimum separation distance). Therefore the separations between the bus stop beacons (Y, Z and AA) in Figure 2 are sufficient to support even same channel simultaneous operation using Class B or C RSU transmitters. If the separation between bus stop beacons is reduced below 57 feet, special RSU antenna or RF shielding will be required to operate using the same frequencies.

If adjacent channels are used, the minimum separation distance drops to less than 9 feet. This calculation assumes that all interference is transmitted and received through the sidelobes of the RSU and OBU antennas. At a range of 9 feet, this assumption is likely to be invalid.

#### **4.5 OFF LINE VERIFICATION TO INTERSECTION BEACONS**

In this section an assessment of the impact of off line verification beacons will be presented. This analysis assumes a scenario similar to the off line verification beacon (Beacon W) shown in Figure 2. The minimum separation distances are calculated between the off line verification beacon and an intersection beacon. The assumptions for the intersection beacons are the same as those used in Section 4.3 with a 50 foot operating range. The assumptions for the off line verification beacon are as follows:

- The operating range of the off line verification beacon is between 6 and 30 feet,
- The RSU antenna has a 20 x 20 degree beamwidth,
- The off line verification beacon is mobile and may be used almost anywhere in or out of the main beam of another fixed beacon, and
- The RSU antenna is not pointed directly towards a fixed beacon.

The assumptions above indicate that the worst case minimum separation distance calculations assume that the interference to and from the off line verification beacon is through its antenna sidelobes. Also, the interference to and from the intersection RSU is through its antenna mainlobe.

The spreadsheets listing the minimum separation distance calculations are listed in Appendix F. Beacon 1 in these spreadsheets is the intersection beacon, and Beacon 2 is the off line verification beacon. The separation distances are calculated for each combination of transmitter and receiver. For example, an uplink on uplink calculation under the column labeled "2 on 1" is the separation distance required between the OBU transmitter operating with Beacon 2 and the RSU receiver of Beacon 1.

The results in Appendix F show clearly that if the same channel is used for both beacons, then the minimum separation distance must be greater than 1/2 mile to eliminate uplink on uplink interference from the OBU responding to the off-line verification beacon on the intersection RSU receiver. Even if adjacent channels are used, the required separation distance due to off line uplink on intersection uplink interference is 356 feet which is greater than the operating range of either beacon.

The minimum separation distance results indicate that an off line beacon must coordinate its transmission with nearby fixed beacons. One method for doing this is to attach an OBU transceiver to the off-line beacon. The OBU transceiver would respond to any beacon within range and request a special time slot for off line verification reading. The fixed RSU could then transmit a response indicating a free communications time slot for the off-line verification beacon. The length of the time slot could be fixed or variable depending on the implementation. The off-line verification beacon would communicate with the desired OBU during the time slot allocated by the fixed RSU. If no nearby fixed RSU is detected by the off-line beacon's attached OBU, then the off-line reader's RSU would operate the same as any fixed beacon's RSU.

Coordination with the nearest fixed beacon does not however eliminate the need for a separate channel for the off-line verification beacon. The fixed beacons in a given area will be designed to avoid interference based on their transmit power levels and desired coverage areas. An off-line verification beacon operating close enough to detect one fixed RSU may still be close enough to interfere with another nearby beacon operating in the same channel as the off-line verification beacon. Therefore, the off-line verification beacon must operate on a channel guaranteed to be separate from any fixed beacon in order to take advantage of the adjacent channel isolation and reduce the possibility of interference.

One factor mentioned in earlier reports [6] is that the OBU responding to an off-line reader will also reflect any energy received from other RSUs operating within its range. This effect is not a problem if the off line verification reader coordinates communications with any fixed beacon within range.

If an off line verification beacon's attached OBU is actually out of range of a fixed beacon, but the OBU being read is within the range of the fixed beacon, then incidental interference may occur. The OBU being read by the off line beacon will reflect the energy received from the fixed beacon while it is responding to the off line verification beacon. From equation 6 it can be seen that the energy returned from an OBU is a function of the 4th power of the range between the OBU and the RSU. Therefore, if a 15 dB signal to interference ratio is required, then the fixed beacon will only be able to receive transmissions from OBUs that are within 42% of the range between the fixed RSU and the OBU responding to the off line reader. Note that no adjacent channel isolation can be applied since the interfering energy is a modulated reflection of the tone from the fixed beacon.

Interference between off line verification beacons and fixed beacons, and the need to coordinate transmissions with nearby fixed beacons, may impose some restrictions on the operation of off line verification beacons. The off line verification beacons should only be operated in short bursts that

gather the intended information from the OBU and then discontinue operation. This will greatly limit the potential for interference with nearby fixed beacons.

## 5.0 EFFECTS OF QPSK UPLINK MODULATION ON DSRC OPERATING RANGES

The default uplink modulation defined in the European DSRC draft specifications is Binary PSK (BPSK). An alternative modulation which will double the uplink data rate on each subcarrier is Quadrature PSK (QPSK). [2] Using the QPSK modulation to double the data rate within the same operating bandwidth, however, requires greater received power to achieve the same bit error rate (BER) as BPSK.

The BER or probability of bit error,  $P_b$ , for BPSK at high signal to noise ratios (SNR) can be approximated [4]:

$$P_b \cong \text{erfc} \sqrt{2 * SNR}$$

where  $SNR$  = the received signal to noise ratio.

The BER for QPSK at high SNRs can likewise be approximated [4]:

$$P_b \cong \text{erfc} \sqrt{SNR}.$$

Therefore, a QPSK receiver requires twice the SNR of BPSK receiver to achieve the same BER (or  $P_b$ ). The effects of this requirement on the operating range of DSRC beacons depend on whether the minimum required transmit power is limited by the downlink or the uplink ( $Pt\_d$  or  $Pt\_u$  in the spreadsheets, respectively).

If the required transmit power for successful downlink,  $Pt\_d$ , is greater than the required transmit power for successful uplink,  $Pt\_u$ , by 3 dB or more, then there is no effect in operating range by switching from BPSK to QPSK modulation. This is the case for many of the short to moderate range beacons. Beacons evaluated in Section 4 whose operating ranges are not affected by switching from BPSK to QPSK are the 50' range in-vehicle signing, exit, bus stop and off line verification beacons.

If  $Pt\_u$  is greater than  $Pt\_d$ , then the operating range of the beacon is reduced when the uplink modulation is switched from BPSK to QPSK. Essentially, the MRSI of the uplink is raised by 3 dB when QPSK is used instead of BPSK. From Equation 6 in Section 2.3, it can be shown that the operating range must be reduced by  $3 \text{ dB} / 4 = 0.75 \text{ dB}$  in order to have a successful uplink if the transmit power remains the same. Therefore the operating range using QPSK is 84% of the operating range using BPSK. The beacons whose operating range will be reduced to 84% of their original operating range by switching to QPSK modulation are the in-vehicle signing and intersection beacons designed to operate up to 100' range. These beacons would now only be able to operate up to an 84' range.

The intersection beacon operating over a 50' range requires 18.33 dBm transmit power for a successful downlink and 17.65 dBm for a successful uplink. Therefore the designed transmit power for the beacon RSU is 18.33 dBm. If QPSK modulation were used on the uplink, then the transmit power required for a successful uplink at a 50' range would be 20.65 dBm which is

2.32 dB higher than the designed transmit power. Therefore, the operating range for the uplink (and thus the link itself) is reduced by  $2.32 / 4 = 0.58$  dB. The resulting operating range is reduced to 87.5% of its original operating range or about 44 feet.

The required transmit powers of most of the beacons analyzed in this report are driven primarily by the required downlink transmit power. Therefore, the operating range of most of these beacons is unaffected by switching the uplink modulation from BPSK to QPSK. Only the longer range beacons whose transmit powers are driven by the power required for a successful uplink are affected by the use of the QPSK uplink modulation. The uplink operating range is only reduced by 1/4 of the change in required SNR (see Equation 6). Therefore the range of the affected beacons is reduced by at most 16% by switching the uplink modulation from BPSK to QPSK.

## REFERENCES

- [1] ARINC, "Spectrum Requirements for Dedicated Short Range Communications (DSRC) - Public Safety and Commercial Applications", Federal Highway Administration, Turner-Fairbank Research Center, July, 1996, 1-55.
- [2] "Road Traffic and Transport Telematics (RTTT) Dedicated Short Range Communication (DSRC) - DSRC Physical Layer using Microwave at 5.8 GHz," Draft European Prestandard, European Committee for Standardization (CEN), Version 4.0, October 1995.
- [3] Van Valkenburg M.E., Reference Data for Engineers: Radio, Electronics, Computer and Communications, Eighth Edition, SAMS Prentice Hall Computer Publishing, 1993, 34-2.
- [4] Stremler, F. G., Introduction to Communications Systems, Addison-Wesley Publishing Company, Reading, Massachusetts, 1982, p. 580 - 596.
- [5] Skolnik, M. I., Introduction to Radar Systems, Second Edition, McGraw-Hill Book Company, New York, 1980, pp. 227 and 232.
- [6] Harvey, B. A., "ATIS Communications Alternatives Test and Evaluation - Tasks D + E: Report on Mitigating Degraded Operation of Vehicle-to-Roadside Communications (VRC) Systems Operating in the 902-928 MHz and 5.850-5.925 GHz Frequency Bands," Technical Report submitted to ARINC Research Corporation by the Georgia Tech Research Institute (GTRI), GTRI Project # A-5108, ARINC Subcontract #310292, under FHWA Contract #DTFH61-94-C-00007, February 14, 1996.



**APPENDIX A**  
**GENERIC CALCULATIONS OF MINIMUM SEPARATION DISTANCES**